Introduction

High-side load switches are popular choices for applications including battery-powered portable devices such as feature-rich mobile handsets, mobile GPS equipment, and consumer entertainment products. This Application Note provides an easy-to-understand, non-mathematical approach to explain the properties of discrete high-side load switches and of the AAT4285 SmartSwitch. The important features and parameters which must be considered throughout the design and selection process will also be described.

Overview

A high-side load switch is controlled by an external enable signal to connect or disconnect a power source (battery or adaptor) to a given load at a set time, as illustrated in Figure 1. Compared to a low-side load switch, a high-side load switch source current to the load, while a low-side switch connects or disconnects the load to ground, and therefore sinks current from the load.

The high-side load switch consists of the following three elements, as illustrated in Figure 2:

1. A pass element, which is essentially an enhanced MOSFET (N-channel or P-channel).

   The pass element is the most fundamental part of the high-side switch. One of the key parameters to consider is the resistance of the switch $R_{DS(ON)}$ while it is ON, which causes a small voltage drop across the pass element while connected to a load. Another parameter is switch leakage current while the switch is OFF, to completely disconnect the power source to the given load.

2. A gate-control block, which provides a voltage to the gate of the pass element to switch it ON or OFF.

   It is also called a level-shift block, because an external enable signal is level-shifted to create a gate voltage high or low enough to switch the pass element fully ON or OFF. During the ON period, the gate control level-shifts EN to produce a high (N-channel) or low (P-channel) gate voltage $V_g$ in order to turn the switch fully ON. Similarly, during the OFF period, the gate control produces a low (N-channel) or high (P-channel) $V_g$ to turn the switch completely OFF.

   Many high-side load switches incorporate a “slew-rate control” or “soft-start” function within the gate-control block. The slew-rate control function limits the $V_g$ ramp-up speed when the switch is turned ON in order to protect the load from an excessive “inrush current” which may cause fault conditions such as latch-up.

![Figure 1: High-Side Load Switch in Power Path Management.](image-url)
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The load is sometimes highly capacitive as well as resistive. When the switch is turned OFF under these conditions, the charges accumulated in the capacitive load are discharged slowly, which may keep the load from turning off completely. To overcome this, some high-side load switches include an “active load discharge” function which provides a current path to discharge the capacitive load quickly when the switch is turned OFF. This is typically accomplished by a small low-side FET.

3. An input logic block, whose main functions are to interpret the enable signal and trigger the gate control block, to switch the pass element ON or OFF.

In certain cases, a buffer is needed between EN and the gate-control block because EN may not provide enough current for the gate control to drive the \( V_G \), in which case the buffer serves as a source of additional driving current.

![Figure 2: A P-Channel FET High-Side Load Switch.](image)

Discrete High-Side Load Switch

As illustrated in Figure 3, the discrete high-side load switch integrates a small N-channel FET (Q1) which drives a large P-channel power MOSFET (Q2). Using a P-channel power MOSFET is usually more cost effective than using an N-channel device in this particular application because the P-channel MOSFET does not require a drive voltage higher than the input voltage.

The resistor R1 (10kΩ ~ 1MΩ typical value) is used to turn off Q2 when Q1 is turned off.

R2 (0 ~ 10kΩ typical value) can be used to soft start the Q2 switch. When the output capacitance \( C_O \) is low, the R2 and Q2 FET parasitic capacitor CRSS ramps up for slow turn on. Normally the value of R2 should be at least 10 times lower than the value of R1 to guarantee Q1 turn on. If excessive overshoot current occurs due to fast turn on, an additional capacitor C1 (typical 1000pF) can be added between the Q2 gate and drain, to slow down Q2’s turn on.

When using R1 and R2, a certain amount of current is lost from the input when the switch is ON. This bias current loss is given by the equation:

\[
I_{\text{BIAS-LOSS}} = \frac{V_{IN}}{R1 + R2}
\]

Bias current loss can be minimized by use of a higher value for R1.
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SmartSwitch Features

Slew Rate Control

The AAT4285 is a slew rate controlled P-channel MOSFET power switch designed for high-side load switching applications; the device’s functional block diagram is shown in Figure 4. The slew rate control feature eliminates inrush current to the capacitive load when the MOSFET is turned on, allowing the AAT4285 to operate with a small input capacitor, or no input capacitor at all. During slewing, the current ramps linearly until it reaches the level required for the output load condition. The proprietary control method works by careful control and monitoring of the MOSFET gate voltage. When the device is switched ON, the gate voltage is quickly increased to the threshold level of the MOSFET. Once at this level, the current begins to slew as the gate voltage is slowly increased until the MOSFET becomes fully enhanced. Once it has reached this point, the gate is quickly increased to the full input voltage and $R_{DS(ON)}$ is minimized.

Figure 4: AAT4285 Functional Block Diagram.
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In many applications it may be necessary to remove and insert modules or pc boards while the main system is still operating. These are considered hot-plug applications. Hot-plug applications require the control of current surges seen by the main power supply, or of the voltage overshoot seen by the card being inserted. The most effective way to control these surges is to slowly ramp the current and voltage applied to the card, similar to the way in which a power supply normally turns on. Because of the controlled rise times of the AAT4285, the device can be used to provide a soft start-up to devices being hot-plugged into a powered system. The AAT4285 rise time is 100μs and it can also limit the inrush current into a 10μF or smaller capacitive load, which is sufficient in most applications. The following formula can be used to estimate the inrush current to the capacitive load during the power up period:

\[ I_{\text{INRUSH}} = \frac{C_L \cdot V_{\text{IN}}}{t_{\text{RISE}}} \]

Where:

- \( I_{\text{INRUSH}} \): Maximum inrush current to the capacitive load
- \( C_L \): Capacitive load value; a capacitive load of 10μF or less is recommended for the AAT4285
- \( V_{\text{IN}} \): Input voltage
- \( t_{\text{RISE}} \): Soft-start rise time; \( t_{\text{RISE}} = 100\mu\text{s} \) for the AAT4285

For example, when \( V_{\text{IN}} = 12\text{V} \) and \( C_L = 10\mu\text{F} \), then

\[ I_{\text{INRUSH}} = \frac{10\mu\text{F} \cdot 12\text{V}}{100\mu\text{s}} = 1.2\text{A} \]

When \( V_{\text{IN}} = 12\text{V} \) and \( C_L = 4.7\mu\text{F} \), then

\[ I_{\text{INRUSH}} = \frac{4.7\mu\text{F} \cdot 12\text{V}}{100\mu\text{s}} = 0.56\text{A} \]

Output voltage and current waveforms that illustrate the turn-on characteristics of the AAT4285 with different capacitive loads are shown in Figures 5 and 6.

**Figure 5: Turn On with \( V_{\text{IN}} = 12\text{V} \), \( C_L = 10\mu\text{F} \), \( R_L = 15\Omega \) (CH1: EN, CH2: \( V_{\text{OUT}} \), CH3: \( I_{\text{OUT}} \)).**

**Figure 6: Turn On with \( V_{\text{IN}} = 12\text{V} \), \( C_L = 4.7\mu\text{F} \), \( R_L = 15\Omega \) (CH1: EN, CH2: \( V_{\text{OUT}} \), CH3: \( I_{\text{OUT}} \)).**
Under-Voltage Lockout (UVLO)

The AAT4285 has an under-voltage lockout function, illustrated in Figure 4. The device operates with input voltages ranging from 3.0V to 13.2V, making it ideal for single- or multi-cell battery-powered applications. In cases where the input voltage drops below 3.0V, the AAT4282 internal MOSFET is protected from entering the saturated region of operation by automatically shutting down. An under-voltage lockout ensures that the power switch is in the off state at power up. The UVLO feature of the AAT4285 also ensures the switch is off after the card has been removed, and the switch remains off during the next insertion. The UVLO feature ensures a soft start with a controlled rise time for every insertion of the card or module.

Fast Load Discharge when Shutdown

The AAT4285 has a fast load discharge function when shut down as shown in Figure 4. This function quickly discharges the load capacitor when the card or module is shut down or removed from the main power supply in order to avoid latch-up and allowing the power to start up properly if the card or module is reinserted or enabled again.

Output voltage and current waveforms that show the turn-off characteristics of the AAT4285 with different capacitive loads are shown in Figures 7 and 8.

![Figure 7: Turn Off with V\text{IN} = 12V, C_L = 10\mu F, R_L = 15\Omega (CH1: EN, CH2: V\text{OUT}, CH3: I\text{OUT}).](image)

![Figure 8: Turn Off with V\text{IN} = 12V, C_L = 4.7\mu F, R_L = 15\Omega (CH1: EN, CH2: V\text{OUT}, CH3: I\text{OUT}).](image)
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Key Parameters for Choosing a SmartSwitch

For high-side load switch designs, the following key parameters should be considered:

1. $I_D$ and $R_{DS(ON)}$

   The first critical parameter is $I_D$. This is a system-level parameter which should be considered at the beginning of the design. The $I_D$ of the high-side load switch is determined by the factors such as the type of MOSFET (N-channel or P-channel), the size of the MOSFET, the physical properties of the bonding wire (length and thickness), the thermal capability of the package and the application ambient temperature.

   The next critical parameter is $R_{DS(ON)}$. The relationship between $P_{D(MAX)}$, $I_{D(MAX)}$ and $R_{DS(ON)}$ is shown in the following equation:

   $$P_{D(MAX)} = I_{D(MAX)}^2 \cdot R_{DS(ON)} = \frac{T_{J(MAX)} - T_A}{\theta_{JA}}$$

   Where:
   - $P_{D(MAX)}$: Maximum power dissipation at $T_A$
   - $I_{D(MAX)}$: Maximum $I_D$ high-side load-switch current capability at $T_A$
   - $R_{DS(ON)}$: High-side switch on-state resistance
   - $T_{J(MAX)}$: Maximum operation junction temperature
   - $T_A$: Maximum ambient temperature
   - $\theta_{JA}$: Thermal resistance from junction to ambient

   By using this formula, the maximum $R_{DS(ON)}$ can be calculated at the desired $I_{D(MAX)}$ and $T_A$ application conditions and can verify if the selected load switch can operate in the safe area.

   For example, if the AAT4285’s $\theta_{JA} = 140^\circ C/W$, $R_{DS(ON)} = 500m\Omega$ maximum at $V_{IN} = 5V$, and $T_{J(MAX)} = 125^\circ C$, and assuming maximum ambient temperature $T_A = 50^\circ C$, then

   $$P_{D(MAX)} = \frac{T_{J(MAX)} - T_A}{\theta_{JA}} = \frac{125^\circ C - 50^\circ C}{140^\circ C/W} = 535.7mW$$

   $$I_{D(MAX)} = \sqrt{\frac{P_{D(MAX)}}{R_{DS(ON)}}} = \sqrt{\frac{535.7mW}{500m\Omega}} = 1.03A$$

   When $I_{D(MAX)}$ is chosen, the lower the $R_{DS(ON)}$ value the better; a lower $R_{DS(ON)}$ will reduce power dissipation in the load switch, reduce the voltage drop between $V_{IN}$ and the load, and relieve the thermal stress to the switch.

2. Dynamic response

   With $I_D$ and $R_{DS(ON)}$ chosen, a designer typically looks at the following six key parameters of the switch: dynamic response, operation voltage range, operation quiescent current, off supply current, off switch current, and package size.

   Dynamic response refers to the time required for the load voltage to rise from GND to full $V_{OUT} (= V_{IN} - I_D \cdot R_{DS(ON)})$, or fall to GND from full $V_{OUT}$, with respect to the changing logic level of EN.

   During the start-up period, the turn-on delay time and rise time can be brief for applications demanding fast response, or relatively long for applications that need soft-start to limit inrush current. During power-down, the turn off delay time and fall time need to be short so that the load can be turned off quickly. If the load has a capacitive element, then the fast shutdown load discharge function can help to reduce fall time.
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3. Operation Voltage Range

The device operation voltage range also needs to be selected correctly to cover the system power minimum and maximum available voltages. The AAT4285 operates from an input range from 3.0V to 13.2V, making it ideal for single or dual cell Lithium-Ion/Polymer battery-powered equipment applications and 3.3V, 5V, or 12V powered systems.

4. Quiescent Current, Off Supply Current and Off Switch Current

The operating quiescent current, OFF supply current, and OFF switch current are also important factors to consider, particularly when designing battery-powered equipment requiring long battery run-time. The operating quiescent current is consumed by the internal circuitry when the switch is ON. The OFF supply current is consumed by the internal circuitry when the switch is OFF. The OFF switch current is passed by the MOSFET to the output when the switch is OFF. The lower the operating quiescent current, OFF supply current, and OFF switch current, the higher the overall system efficiency. This results in longer battery run time for portable applications. The AAT4285 has very low operating quiescent current (typically 25μA), off supply current (maximum 1.0μA) and off switch current (maximum 1.0μA).

5. Package Size

The package size (footprint and profile) is important; in most portable applications, a smaller package is preferred because space is at a premium. The AAT4285 is available in the very small 8-pin SC70JW package, which has a 2.2mm x 2.0mm footprint.

Conclusion

Features of the AAT4285 SmartSwitch include slew rate control, UVLO, and fast load discharge when shut down. It is an ideal choice for a high-side load switch in battery-powered applications or hot-plug cards or modules.